STRATIGRAPHY AND HYDROTHERMAL ALTERATION OF WELL OW-601 OLKARIA GEOTHERMAL FIELD, KENYA

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ABSTRACT

Well OW-601 is the sixth well drilled as an exploratory well in the Olkaria West field. The well was drilled to a depth of 2600 m in order to delineate the field and also to investigate the deep low resistivity found in this area. The latest temperature runs taken after two months of heating gave a temperature of 326°C at 2600 m depth. During drilling no loss zones were encountered below 400 m depth. Completion and reinjection tests carried out did not show any dominant permeable zones.

The rocks penetrated are dominantly lava rocks with tuffaceous intercalations. Petrographically the rocks are similar to those encountered elsewhere in the Olkaria geothermal area. The rocks show extensive alteration which is comparable to that of other wells in this field but higher than that of Olkaria East field. The hydrothermal alteration mineral assemblage encountered in this well indicates high temperatures. Calcite and clay minerals are the most abundant hydrothermal alteration minerals. They occur from the first indication of water/rock interaction to the bottom of the well. The abundance of calcite which is similar to that encountered in well OW-301 indicates that high CO_2 concentrations may be expected expected in the steam. Fluorite is most abundant in acid rocks in the lower rhyolites. The occurence of zeolites is sporadic. Biotite occurs at depths where inferred temperatures are below 200°C. Actinolite which has not been reported before in the Olkaria geothermal field occurs below 2296 m depth. The occurence of wollastonite in the actinolite zone is tentative as it was not confirmed in thin section analysis. Epidote occurs in two zones but is more abundant in the lower zone below 1800 m depth.

Four alteration zones were established and the inferred temperatures are higher than measured temperatures after two months of heating. The alteration zones indicate a temperature of 200°C at 740 m depth and temperatures in excess of 300°C below 2296 m depth. Crosscutting and infilling sequences were studied in order to reveal the thermal history of the area. However, the data available was not sufficient to form a comprehensive study.

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1 INTRODUCTION

1.1 Scope of study

The author of this report was awarded a six month UNU Fellowship to study borehole geology at the 1985 UNU Geothermal Training Programme held at the National Energy Authority of Iceland. During the course, about five weeks were spent attending introductory lectures on all disciplines involved with geothermal energy exploration, exploitation and utilization, one week on literature related to borehole geology, two weeks on XRD practice, and a one week excursion to an extinct and deeply eroded central volcano (Geitafell) in SE Iceland. About two weeks were spent analysing cuttings of selected samples from Nesjavellir well NJ-11. During the same period a few samples from the same well were analysed for clay minerals using the XRD method. A further two weeks were spent on a UNU excursion which covered many of the geothermal fields in Iceland. The areas visited included both low and high temperature geothermal fields.

After the excursion five weeks were spent analysing samples from Olkaria well OW-601 and Nesjavellir well NJ-12. The samples from Nesjavellir were used as study material in identification of alteration minerals. Samples from Olkaria well OW-601 were used as material for this report. The rest of the course period was used mainly for the preparation of this report and in discussions with the supervisors.

1.2 The project area

The Olkaria Geothermal Area is located within the eastern arm of the African Rift Valley (Fig. 1). It is one of several geothermal areas occuring within the Rift Valley and the only one that has been developed with a power station rated at 45 MWe in operation.

For the purpose of development the area has been divided into two fields; Olkaria East and Olkaria West. The Olkaria East field is developed where a total of 25 wells have been drilled and at present 21 are on line. Lithological and hydrothermal alteration studies for this field have been carried out (Browne, 1981). The Olkaria West field is under exploration, and so far only 6 wells have been drilled, out of which 4 have been logged (Muchemi, 1984 and 1985; Odongo, 1984).

The area is covered by Quaternary ash and pyroclastics and as such the area is poor in outcrops. The only outcrops encountered are the comendites (sodic-rhyolite) cliffs of Hell's Gate (Ol'Njorowa Gorge) and Recent lava flows overlying the pyroclastics (Naylor, 1972). However, downhole the lavas constitue about 90% of the rocks. The rocks in the area include basalts, trachytes, rhyolites, comendites, tuffs and pyroclastics. Of these the trachytes are predominant by volume. A lithological correlation of the Olkaria East has been carried out by Browne (1984a). However, difficulties have been realised due to the small grainsize of the cuttings and the masking of details by alteration (mainly Fe-oxides).

In the Olkaria Geothermal Field, hydrothermal alteration is observed throughout the penetrated rock units with the exception of the surface pyroclastic layer. The intensity of alteration increases markedly below 550 m depth (Browne, 1981). Above this zone oxidation predominates except on fault/fracture zones and around fumaroles where hydrothermal alteration is observed on the surface. In general the lavas encountered in the Olkaria East field show little fluid/rock interaction and alteration minerals are found mainly in veins. In the Olkaria West field the rocks encountered generally show a higher intensity of alteration.

The hydrothermal mineral assemblage includes; sheet silicates, zeolites, chalcedonic silica, quartz, calcite, albite, Fe-oxides, adularia, pyrite and epidote. Chlorites are the most common alteration minerals except where oxides predominate. Epidote and calcite are more common in the basalts where measured temperatures are below the stability limit (250-260°C) of epidote (KPC, 1984). This has lead to the conclusions that the field has either experienced thermal reversals (Browne, 1981), or that the presence of epidote is due mainly to the bulk chemistry of the basalts (KPC, 1984).

1.3 Well OW-601

The present report discusses well OW-601 drilled in Olkaria West field as an exploration well (Fig. 2). The well was drilled to a depth of 2600 m and is to date the deepest well drilled in the Olkaria geothermal area. The well was sited in an area with no known fault zones so as to test the high temperature reservoir indicated by well OW-301 and also to investigate the deep low resistivity present in this area (KPC, 1984). At the same time the well was drilled to this depth so as to give a view of the stratigraphy and alteration of this area at depth.

During drilling a circulation loss was encountered from 48-400 m depth. It is possible that this loss is due mainly to the loose pyroclastic layer found at shallow depth which is probably smaller than indicated above. This is supported by the fact that the end of the loss zone coincides with the anchor casing shoe (at 400 m depth), and that a core taken at 87 m depth was identfied as a rhyolite. The well was drilled with water and mud above the production casing shoe (800 m depth) and with water only below this casing shoe. Below 400 m depth no circulation loss zones were encountered. However, the absence of loss zones is not conclusive as only visual methods were used for the detection of loss zones. Completion tests carried out after drilling were unsuccessful as the well could not take water at pump pressures of up to 600 psi. At the time of writing this report no geochemical data was available. However, well OW-301 drilled in the Olkaria West field and which shows a similar abundance of calcite to well OW-601, has high CO_2 concentrations in steam, about 15%, (KPC, 1985) and bicarbonate waters. This therefore indicates that similar conditions may be expected in well OW-601.

2 STRATIGRAPHY

During the drilling of well OW-601 cuttings were collected at two meter intervals. However, for the present report sampling was done at approximately ten meter interval and as such the lithological log presented here is not as continuous as the available samples. Ten core samples were also available for the interpretation. Fig. 3 shows the stratigraphic interpretation correlated with hydrothermal alteration and alteration zones.

The rocks encountered are predominantly lava rocks with tuffaceous intercalations. The basalts and the rhyolites are the most dominant rocks by volume. Petrographically the rocks are similar to those encountered elsewhere in the Olkaria geothermal area, but a stratigraphic correlation with other Olkaria West wells is difficult as shown in Fig. 4. This is due to the uncertainities in the lithological interpretation of the earlier wells as they were drilled near or within fault zones. Also the poor recovery of cuttings during drilling of these wells made the location of samples unreliable. However, this well shows a close relationship in stratigraphy to well OW-301 (Fig. 4). Below is given a summary of the stratigraphy.

Pyroclastics: These extend from the surface to the top of the Upper Rhyolite. This unit consists of pumice, obsidian, and euhedral crystals of quartz and feldspar (sanidine). The unit is unindurated and shows no alteration.

Upper Rhyolites: These occur at 48-486 m, and at 750-798 m depth. These are mainly spherulitic rocks with some zones showing flow banding. The rocks are porphyritic with feldspar (sanidine) and quartz phenocrysts. Also present are small but abundant phenocrysts of pyroxene (aegerine), rare amphibole (riebeckite) and magnetite. The rocks are rather fresh but the glassy bands show slight alteration to clay (smectite). The lower part at around 498 m depth shows veins filled by calcite.

Upper Basalts: These occur at 582-610 m, and at 718-750 m depth. These are fine to medium grained porphyritic (plagioclase) olivine basalt with abundant augite and magnetite. The rocks show extensive alteration (602 m). The plagioclase shows alteration to smectite, illite and calcite around the margins and in cracks. However, all the olivine has been replaced by the clay minerals and calcite. Biotite occurs in this zone as an alteration mineral. Veins are filled by calcite.

Trachytes: These occur at 798-946 m, and at 1424-1460 m depth This unit is fine grained and consists of feldspar (sanidine) phenocrysts showing Carlsbad twinning and a plagioclase groundmass. Where fresh, the rock contains riebeckite and augite. It is extensively altered with some of the feldspars partially replaced by calcite and clay minerals. The veins are filled mainly by calcite, but zoning of smectite and quartz was observed. Albite occurs in these rocks as a replacement of K-feldspars.

Lower Rhyolites: These occur intercalated with tuffs at 994-1366 m, 1484-1552 m, 1598-1616 m, 1628-1798 m, and at 2518-2558 m depth. These are distinguishable from the Upper Rhyolites by the lack of spherulitic texture, poor phenocryst content, and also by the lack of magnetite. The rocks are felsic, medium to coarse grained, and contain phenocrysts of quartz and sanidine. Calcite occurs as a vein filling and also as a replacement of feldspars.

Lower Basalts: These occur at 1460-1484 m, 1552-1598 m, and intercalated with tuffs at 1798-2458 m depth. These are fine grained olivine basalts lavas consisting of plagioclase phenocrysts and a plagioclase rich groundmass. They are extensively altered showing complete replacement of olivine by calcite and clay minerals (chlorite and illite). The feldspars show partial replacement by chlorite and illite. The rocks are commonly vesicular with the vesicles filled by sphene, epidote, quartz and chlorite.

Tuffs: These are common and vary from wholly glassy showing flow banding to welded tuffs containing lithic and feldspar fragments. They vary in thickness from less than 10 m to about 100 m. In most cases it was observed that these two variations occur in bands within the same horizon. The glassy bands are mainly brownish to greenish in colour due to alteration of the glass to smectite and chlorite whereas the bands containing rock fragments show alteration mainly to smectite which imparts a brownish colour to the rock. The smectite in the brownish bands tend to mask most of the details. In the brownish bands calcite occurs mainly as a vein filling mineral.

Dolerite: This was encountered at the bottom of the well. It is a coarse grained aphyric rock showing extensive alteration. The rock consists of plagioclase felspars which show alteration to clay minerals (chlorite and illite), calcite, long prismatic crystals of apatite and relict pyroxenes which have been replaced by clay minerals. The rock shows a similar intensity of alteration to the lava rocks. However, epidote was not observed in the rock. Dolerite has not been reported before in the Olkaria geothermal area, but gabbro intrusives occur in the Olkaria East field (Browne, 1984a).

3 HYDROTHERMAL ALTERATION

3.1 Analytical techniques

The occurrence and distribution of hydrothermal alteration minerals is shown in Fig. 3. The samples were analysed using binocular microscope, thin sections and XRD analyses. The XRD analyses were carried out mainly for the determination of clay minerals as the cuttings were too fine to handpick alteration minerals. The presence of felsic rocks in the cuttings made the handpicking of alteration minerals even more difficult as it was hard to distinguish alteration minerals from acid rock cuttings. However, alteration minerals were handpicked from four samples (at 1918 m, 2126 m, 2186 m, and 2368 m depth) and ran as bulk powder samples. A total of 33 samples were run on XRD for clay analysis.

The method practised in Iceland for clay mineral analysis on XRD was used in the present study (Hardardottir, 1984). The method is described below:

1. The samples are put into a test tube and cleaned with distilled water. The test tubes are then filled with distilled water and put in a shaker for about 24 hours or longer depending on whether enough clay minerals are present in the water.

2. The samples are allowed to settle for 1-2 hours. The solution is then pipetted onto a glass plate and allowed to dry at room conditions and then run on XRD from 2-17°.

3. The samples are placed in a dessicator containing $CaCl_2$, to maintain humidity at 35%, for 24 hours and then run on XRD from 2-17°.

4. The samples are placed in a dessicata containing ethylene glycol for 24 hours and then run from 2-17°.

5. The samples are placed in an oven maintained at 550-600°C for about 1-1.30 hours and then run from 2-17.

The results of the XRD analysis for clay minerals are shown in Appendix 1. The intensities shown were calculated taking the width of the graph paper as 100% when the range of the XRD machine was set at two (R = 2). It was noted that some of the peaks interpreted as chlorite show an increase in d values after heating. An example of this is shown in Fig. 5(c). Figures 5(a) and 5(b) show characteristic peaks for smectite and illite respectively.

3.2 Alteration of primary minerals

Calcite and clay minerals are the most common replacement of the primary minerals. Others include albite and quartz. In the acid rocks, the most altered primary minerals are the pyroxenes and feldspars whereas quartz is relatively unaltered but is in some cases dotted with clay minerals. In the basic rocks olivine and glass are completely replaced by clay minerals and illite whereas the plagioclase feldspars and the pyroxenes (augite) are only partially replaced. In the trachytes it was observed that the feldspar phenocrysts (sanidine) show a stronger alteration than the plagioclase matrix. The sanidine shows replacement by calcite, clay minerals and albite. In general, the order of decreasing susceptibility to alteration is: glass, olivine, pyroxene, K-feldspar, plagioclase and quartz. This observation agrees with the sequence observed in Olkaria East field, (Browne, 1984a).

3.3 Distribution of hydrothermal alteration minerals

The hydrothermal alteration mineral assemblage found in this well include; calcite, chlorite, smectite, opal, illite, epidote, pyrite, wollastonite, albite, wairakite, prehnite, adularia, stilbite, fluorite, biotite, sphene and actinolite and is similar to that found in other high temperature geothermal fields (Browne, 1978). Fig. 3 shows the distribution and occurence of hydrothermal alteration minerals compared to the lithology and alteration zones. Zeolites which have been described in the Olkaria East field are rare in this well. Calcite and clay minerals (smectite, chlorite and illite) are the most abundant hydrothermal alteration minerals occuring in this well. Smectite and calcite appear at the first indication of water/rock interaction.

Calcite is one of the most abundant hydrothermal alteration mineral in the well. It occurs at the first onset of fluid/rock interaction. At shallow depths within the smectite zone, it occurs as a vein and amygdale infilling and in most cases it is the only alteration mineral observed in veins. At deeper levels within the chlorite zone calcite occurs also as a replacement of primary minerals. Two generations of calcite were identified in vesicles at about 2300 m depth (Fig. 6).

Chlorite traces were first observed in thin section at 518 m depth. However, in XRD analysis traces of chlorite were first seen at 740m depth and it persists to the bottom of the well. It is more abundant below 1258 m depth where chlorite and illite are the most dominant clay minerals. Near the bottom of the well (below 2560 m depth) XRD analysis show a decrease of chlorite although in thin section it is seen to be abundant. However, it was also observed that the chlorite shows alteration to amphiboles at this depth. Chlorite occurs mainly as a replacement of primary minerals (feldspars and olivine), and also as an amygdale infilling.

Epidote occurs in two zones, the first zone extends from 850 m - 1198 m depth, and the second and most prominent zone extends from 1800 m - 2598 m depth. A core taken at 2600 m depth does not show the presence of epidote and therefore the lower boundary of epidote could be a bit higher than indicated by cutting analysis. In the upper zone it occurs as massive aggregates whereas in the lower zone it occurs in radiating prismatic aggregates. It mainly occurs as a vesicle infilling and rarely as a vein filling mineral.

Pyrite was first encountered at 714 m depth and it persists to the bottom of the well. However it is most dominant within the acid rocks where it occurs in well crystalline cubic crystals which are up to 1 mm in size.

Wollastonite is very rare and was observed only in cutting analysis as a white fibrous mineral between 2296 m and 2344 m depth and was not confirmed in thin section.

Quartz occurs mainly in cavities, as a replacement of primary minerals (feldspars in acid rocks) and also as a vein filling mineral forming zones with chlorite and calcite (core at 1996 m depth). The first occurrence is at 550 m depth and it persists to the bottom of the well.

Opal (chalcedony) first occurs at 400 m and is most abundant at 2300 m depth where it forms zones with chlorite. The zones show chlorite on the outside and opal on the inside. The opal shows alteration to chlorite.

Illite is very abundant and it occurs from about 480 m depth to the bottom of the well. It was first detected by XRD analysis at 534 m depth and is most abundant in the acid rocks where it occurs as a replacement of K-feldspars (1645 m depth). Illite occurs as a vein filling mineral, vesicle infilling, and also as a replacement of primary minerals.

Prehnite was observed to occur between 2150 m and 2478 m depth. Its occurence is sporadic and it was only encountered as individual grains which do not show the relationship to other alteration minerals.

Albite occurs as a replacement of primary feldspars (K-feldspars and plagioclase). It first appears at 600 m depth as detected in petrographic analysis and is also found in the Lower Basalts.

Fluorite occurs as a cavity filling and is most abundant in the acid rocks. It first appears at 1920 m depth and is continuous to 2050 m depth. It forms zones with calcite where calcite deposits at a later stage.

Smectite is the most prominent clay mineral ocurring above 550 m depth. However, downhole smectite occurs to about 1103 m depth although it is not detected by XRD analysis below 690 m depth. Below this depth smectite occurs in narrow zones in tuffs and volcanic glass (1103 m) as an alteration product of volcanic glass, in vesicles and as a vein infilling and also as a replacement of primary minerals. In veins it forms zones ranging in colour from red brown in the outer zone to yellowish brown in the inner zone. It also forms zones with calcite where the yellowish brown zone is older than calcite.

Biotite occurs in well formed crystals but was only encoutered in one core sample taken at 602 m depth.

Actinolite occurs first at about 2296 m depth in cuttings but in thin sections it was detected at 2600 m depth where it occurs as a replacement of chlorite.

Sphene occurs first at 1618 m depth and continues to the bottom although it was not seen in a core taken at 2600 m depth. It occurs filling cracks in feldspars and also as a vesicle and vein infilling. In veins and vesicles sphene occurs as the earliest infilling after Fe-oxides. It forms zones with epidote, calcite, and opaque oxides (rare).

Wairakite is rare and was not adequately determined in thin sections.

Adularia occurs mainly as a replacement of K-feldspars but was also observed filling cavities of leached feldspars. Where it occurs in leached feldspar, the crystals were too fine to be properly determined.

Stilbite was observed mainly in the rhyolites and tuffs (1038 m depth). It occurs in radiating cloudy crystals due to replacement by clay minerals.

3.4 Alteration zones

In earlier studies hydrothermal alteration minerals have been used to predict conditions existing in a hydrothermal system at the time of their deposition. Inparticular temperature, pressure and chemistry of a system can be deduced from alteration minerals. In geothermal systems pressure has been found to be of minor significance to the deposition of hydrothermal alteration minerals (Bowne, 1978), except where a decrease in pressure causes the deposition of calcite. The chemistry of the rocks also contributes to the deposition and therefore certain minerals are more common in some types of rocks than others, e.g. low silica zeolites in geothermal fields of Ice land where the rocks are predominantly basaltic as compared to mordenite which is more common in rhyolitic fields (Browne, 1984b). The occurence of adularia has been used to denote permeable zones (Browne, 1978). The minerals mostly used for the prediction of temperatures are clay minerals, epidote, prehnite, wollastonite and amphiboles. The first appearance of these minerals is used to establish hydrothermal alteration zones which can be used to produce isotherms and compare with measured temperatures.

The application of clay minerals in the establishment of alteration zones was demonstrated by Kristmannsdottir (1976), where clay mineral zones in a high temperature geothermal field in Iceland are shown to conform con siderably well with measured temperatures. In well OW-601 four hydrothermal alteration zones have been established (Fig. 3). The first three zones are based on clay mineralogy, namely, smectite, illite and chlorite. The fourth zone is based on the appearance of actinolite which has been reported to form hydrothermally at temperatures above 300°C (Browne, 1978 and Kritmannsdottir, 1979).

<ins>(a) Smectite zone:</ins> This extends from the surface to about 534 m depth where illite is first encountered. In this zone smectite is the most dominant hydrothermal alteration mineral. Other alteration minerals in this zone include calcite and iron oxides. The primary minerals in this zone show little hydrothermal alteration and smectite occurs mainly as an amygdale infilling, and also as an alteration product of volcanic glass. In thin section smectite was observed to a depth of 1103 m but in XRD analysis it was not detected below 690 m depth.

<ins>(b) Illite zone:</ins> Illite first occurs with smectite at about 534 m depth, and continues to the bottom. The lower end of the illite zone is here defined as the first appearance of chlorite at 740 m depth. In this zone other alteration minerals include calcite, smectite, biotite,

rare adularia and albite. Illite in this zone occurs as a replacement of feldspars, olivine, pyroxene and also as a vein filling mineral together with calcite.

<u>(c) Chlorite zone:</u> This extends from 740 m depth where chlorite is first detected to 2296 m depth where actinolite was first seen. This zone is marked by a stronger intensity of alteration and an increase in hydrothermal alteration mineral assemblage. The alteration minerals in this zone include illite, calcite, epidote, sphene, albite, adularia, fluorite, pyrite, quartz, opal and wairakite. In this zone chlorite occurs as an amygdale infilling and also as a replacement of primary minerals (feldspars, olivine, and pyroxenes). Although chlorite occurs to the bottom of the well, a decrease in XRD peak intensity was detected below 2488 m depth.

<u>(d) Actinolite zone:</u> This zone is indicated by the occurence of the amphibole in cuttings at 2296 m depth. However, it was not detected in XRD analysis and was only seen in thin section at 2600 m depth. Wollastonite was also observed in this zone although it was not confirmed in thin section. Otherwise the hydrothermal alteration mineral assemblage occuring in this zone is similar to that found in the chlorite zone.

3.5 Mineral evolution

In determining the evolution of a hydrothermal system the mode of occurence of alteration minerals is of great importance. As a hydrothermal system requires a fluid for the transportation of elements, and as mineral deposites depend on temperature and chemistry of the system at that time, it follows that the evolution of a hydrothermal system can be unravelled by the study of hydrothermal alteration minerals occuring in veins and vugs. In doing this the deposition sequence of minerals is established.

In this report an attempt was made to evaluate the evolution of the system. However, the samples available were too fine in grain size and too few in number to allow a comprehensive study. Examples of mineral relationships used in this study (Fig. 6) were derived from two core samples taken at 1996 m and 2300 m depth. The relationship shown here indicates that sphene is the oldest phase in both cases. Calcite occurs in two generations where the earlier phase is deposited after quartz and the latter phase appears in cases to be the replacement of clay minerals. Where the quartz phase occurs it is very thin and discontinuous. Epidote is of an earlier phase than calcite and later than quartz.

The veins are generally filled by calcite where the walls are zoned by the clay minerals in the smectite and the illite zone but in the chlorite zone the walls are zoned by sphene. The sphene is probably a replacement of Fe-oxides of an earlier infilling phase.

4 DISCUSSION

The well under study was drilled as an exploration well to determine the northern extent of the geothermal resource and also to test resevoir conditions at depth outside known fault zones. At the time of writing this report the highest temperature measured in the well was 326°C at 2600 m depth after two months of heating. Fig. 7 shows the latest temperature run compared to a calculated temperature profile based on boiling temperature for measured pressure.

The rocks encountered in this well are similar to those occuring elsewhere in the Olkaria geothermal area. A lithological correlation between well OW-601 and wells drilled in Olkaria West (Fig. 4) is difficult due to the location of wells on fault zones and unreliable sample locations. However, this bears a close relationship in stratigraphy to well OW-301 as shown in Fig. 4. This well differs lithologically from the other wells in that the trachytes which have been reported to be dominant lava rocks in the Olkaria East field (Browne, 1984a) are lesser in volume than the other lava rocks.

The rocks show extensive alteration and water/rock interaction was observed below 400 m depth. The intensity of alteration is comparable to that found in well OW-301 and is higher than that encountered in the Olkaria East field where the rocks show little fluid/rock interaction (Browne, 1984a). Clay minerals (smectite, illite and chlorite) and calcite are the most abundant hydrothermal alteration minerals. The hydrothermal alteration mineral assemblage is similar to that found in other wells in the Olkaria geothermal area. However, in the Olkaria west field epidote is reported to occur only in well OW-401. The occurence of epidote in two zones in this well is possibly due to the chemistry of the rocks. It is notably absent where the acid rocks are dominant. The occurence of biotite at 602 m depth is anomalous as biotite is reported elsewhere to occur at temperatures above 280°C (Browne,1978). Its presence in this well at this depth could be due to an intrusive rock which was not detected in petrographic analysis. Wollastonite and actinolite found in this well below 2296 m depth have not been reported before in the

Olkaria geothermal area. The occurence of wollastonite is however tentative as it was not confirmed in petrographic or XRD analysis. This could be due to the fact that with the exception of wells OW-19 and OW-401, where sample recovery was poor, all the other wells were shallower than this depth. Clay minerals have not been studied in detail before and therefore a correlation of alteration zones is not possible at present.

The hydrothermal alteration mineral assemblage indicates a high temperature geothermal system. This is shown by high temperature minerals such as chlorite, epidote, wollastonite, prehnite, and actinolite (Kristmannsdottir, 1982). However, these minerals have also been reported to occur below projected equilibrium temperatures. Thus the presence of these minerals does not necessarily indicate present temperature conditions but existing temperatures at the time of their formation. Examples of this is in Iceland, where epidote is reported to occur below 250°C (Kristmannsdottir, 1982), and Olkaria East field where epidote is encountered at about 200°C (Browne, 1984a). Chlorite has also been reported to occur at temperatures below 200°C (Browne, 1978).The progressive transition of clay minerals with increasing temperature has been used in other geothermal areas to predict reservoir temperature. In the New Zealand geothermal fields the transition of Ca-montimorillonite to illite and chlorite is reported to occur at 220°C (Browne, 1978). A similar transition of clay minerals with increasing temperatures has been observed in the Philippines geothermal fields (Reyes and Tolentino, 1981). These observations have been used in this report to predict reservoir temperatures.

Taking 200°C as the lowest temperature at which chlorite forms (Kristmannsdottir, 1979), then the 200°C isotherm can be taken as the upper boundary of the chlorite zone at 740 m depth. By the same argument the abundance of chlorite at 1258 m depth indicates that the temperature at this depth is above 200°C. The occurence of epidote at 850 m depth, and its abundance below 1800 m depth indicates that temperatures in this zone are above 250°C. The occurence of wollastonite and actinolite at 2296 m depth would indicate temperatures in excess of 300°C (Kristmannsdottir, 1981). However, recent studies in Iceland show that wollastonite occurs at about 270°C (Franzson, personal communication). These temperature predictions do not correlate with measured temperatures taken after two months of heating. However, they are within the calculated boiling temperature for measured pressure curve shown in Fig. 7. The abundance of calcite in the well is comparable to that in well OW-301 where high CO_2 gas ratios were measured in steam (KPC, 1985). This possibly accounts for the rare occurence of zeolites as suggested by Kristmannsdottir (1982). Ellis and Mahon, (1977), have also shown how the preferential deposition of calcite inhibits the formation of Ca-silicates.

5 CONCLUSIONS

The lithological units encountered in this well are similar in petrography to those of other Olkaria wells. The basalts and the rhyolites are the most dominant lava rocks. The intensity of alteration is higher than that of the Olkaria East wells but similar to that of other Olkaria West wells. The deep low resistivity present in this area is possibly due to the abundance of clay minerals in this well.

The hydrothermal alteration mineral assemblage indicates a high temperature geothermal field. Clay minerals and calcite are the most dominant hydrothermal alteration minerals. The abundance of calcite indicates that high CO_2 concentrations are expected in steam and thus calcite scaling during the exploitation of this well. The rare occurence of zeolites is possibly due to high CO_2 partial pressures. Epidote is more abundant below 1800 m depth. The occurence of biotite at 602m where temperatures are below 200°C is anomalous. The occurence of wollastonite was not adequately confirmed and therefore further investigations are required. Actinolite which has not been reported before in the Olkaria geothermal area occurs below 2296 m depth.

Four alteration zones, smectite zone, illite zone, chlorite zone, and actinolite zone, were recognised. The temperatures inferred from these zones indicate that temperatures are about 200°C at 740 m depth and in excess of 300°C below 2296 m depth which is higher than measured temperatures after two months of heating.

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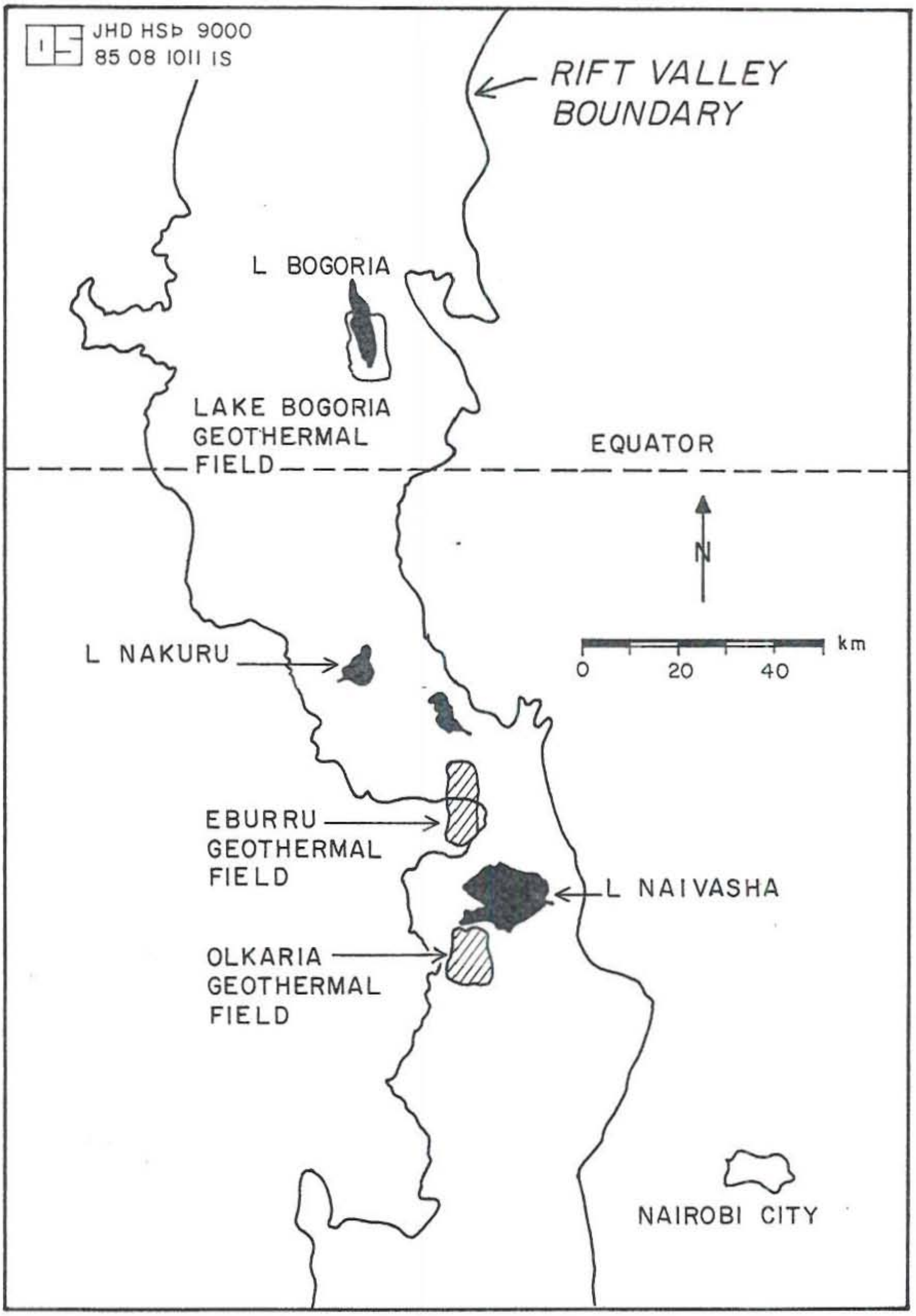

Fig. 1. The location of the Olkaria geothermal area within the Rift Valley.

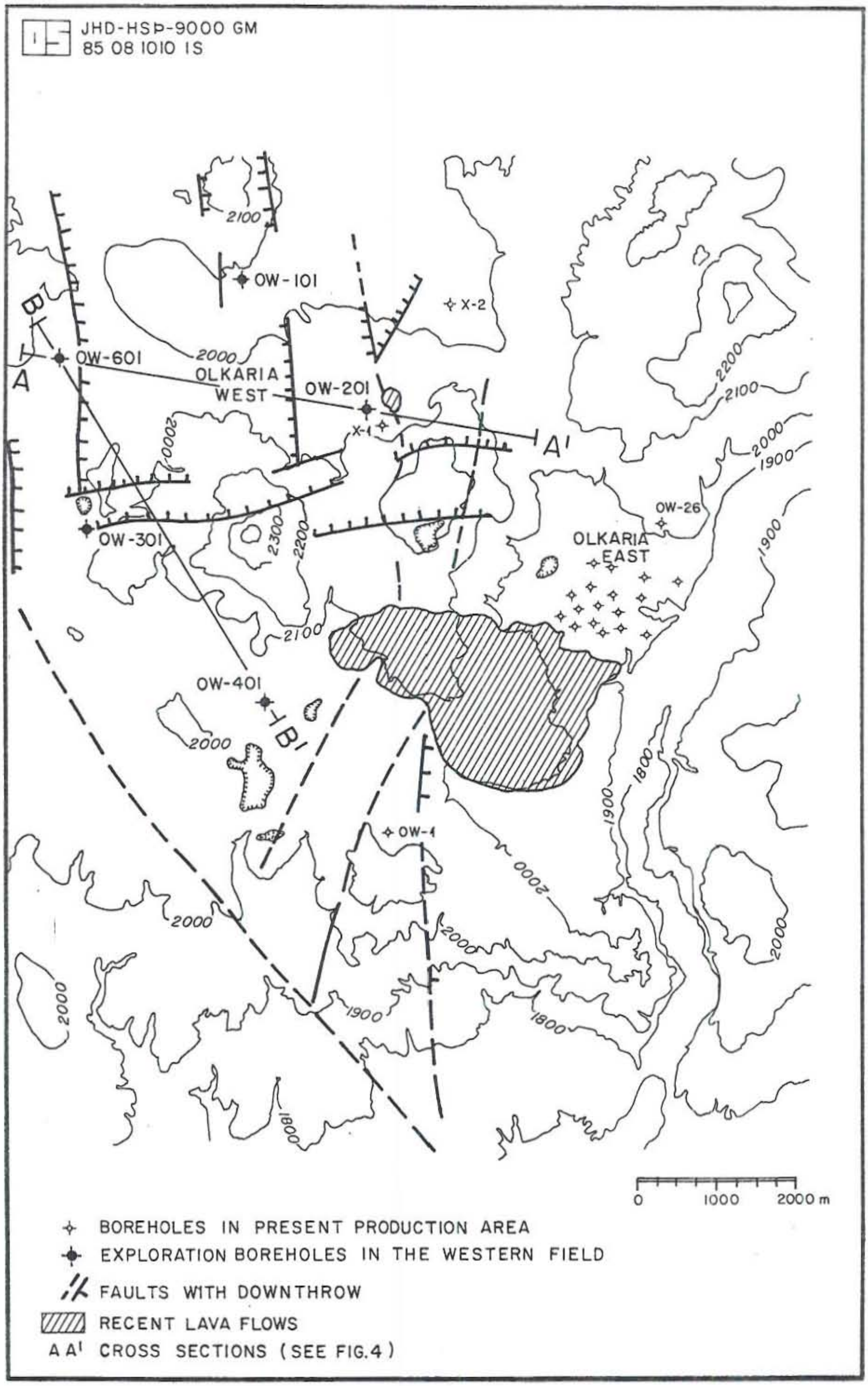

Fig. 2. The Olkaria geothermal area.

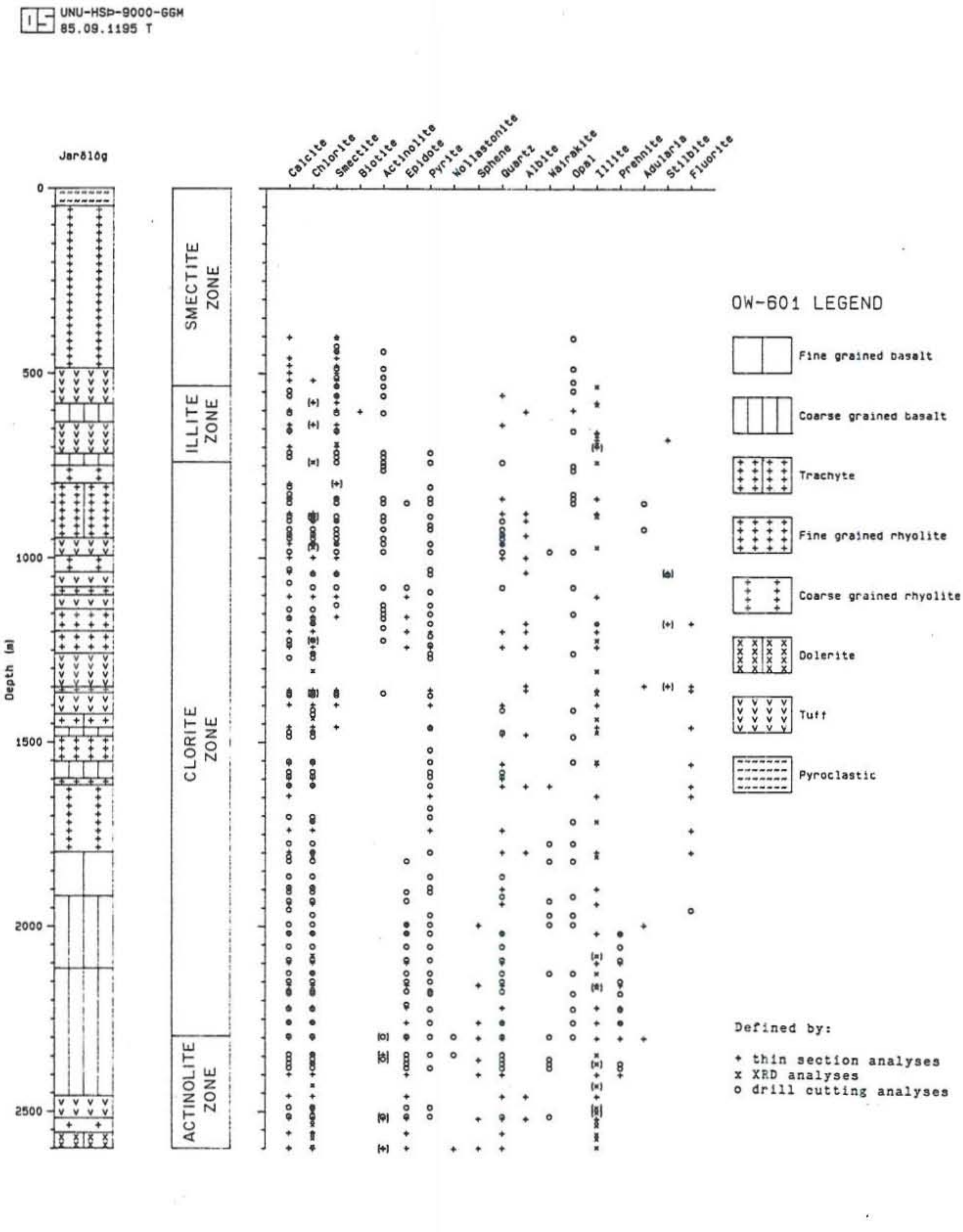

Fig. 3. Stratigraphy and hydrothermal alteration of well OW-601.

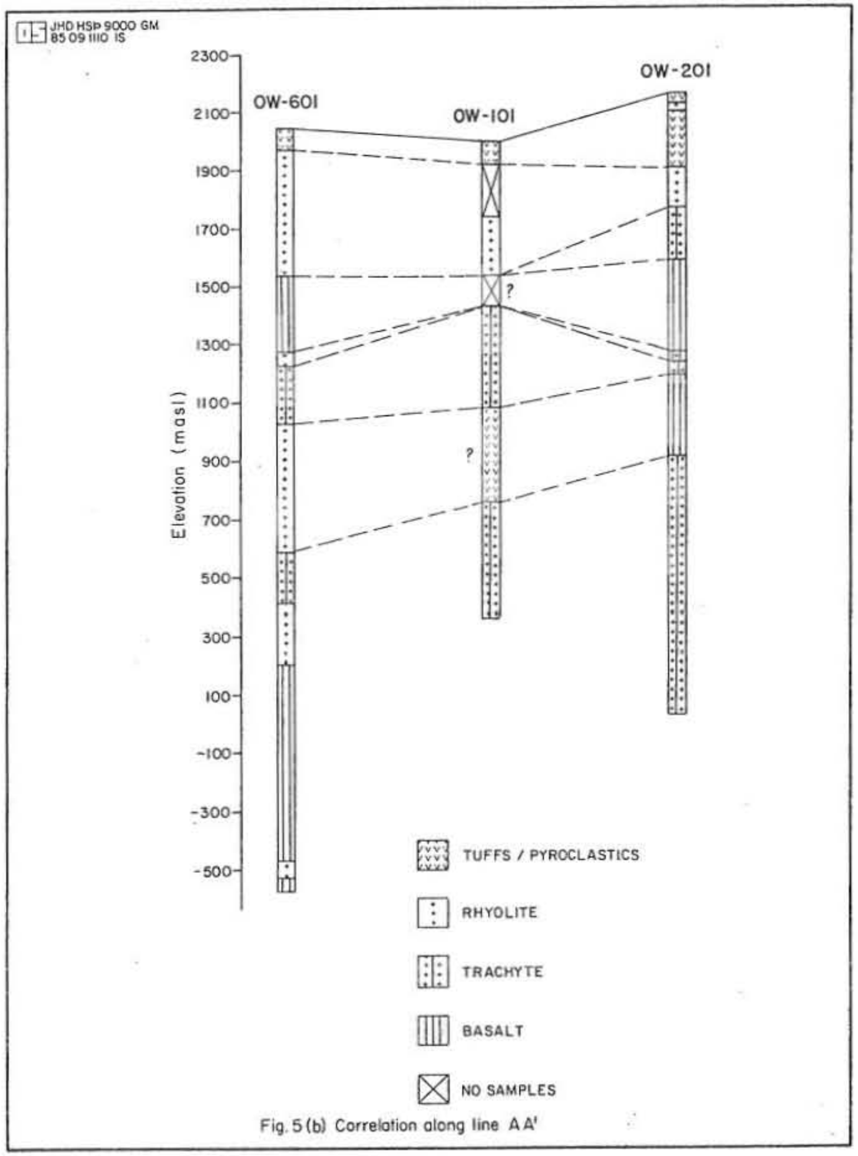

Fig. 5 (b) Correlation along line AA'

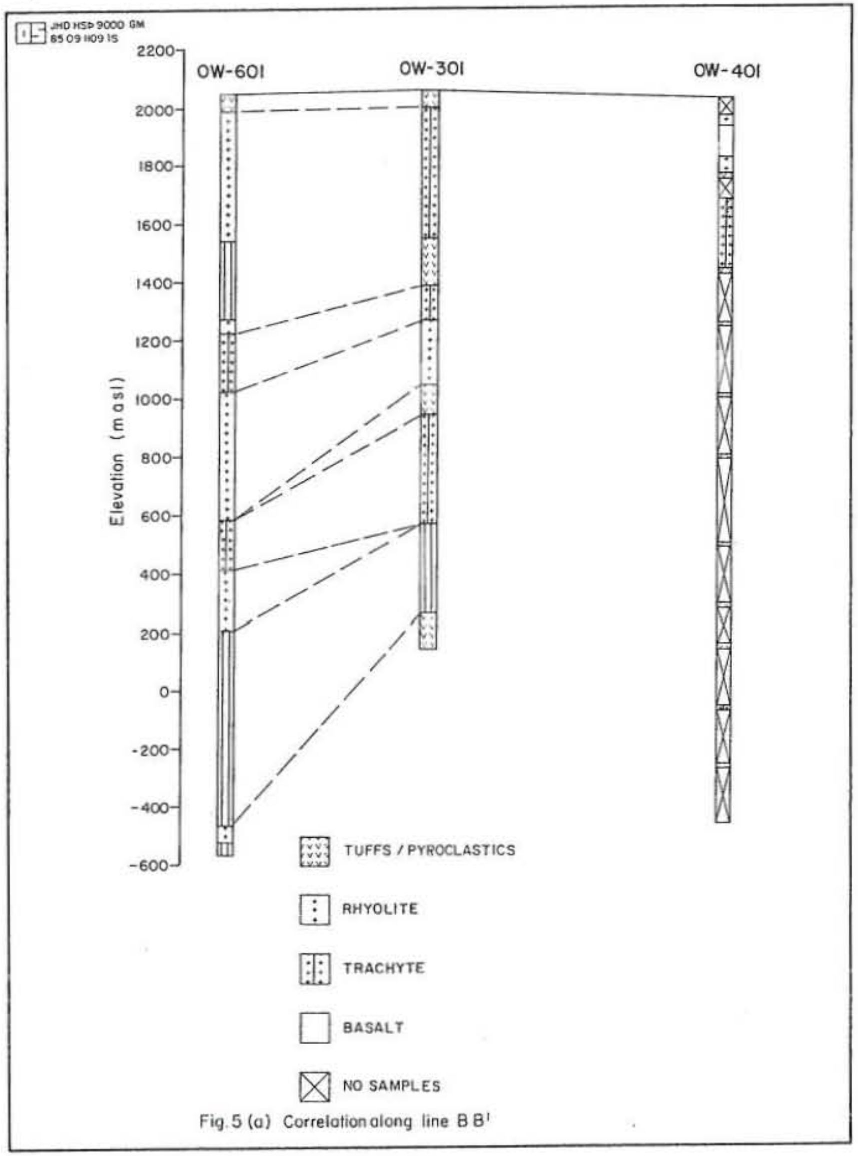

Fig. 5 (a) Correlation along line BB'

Fig. 4. Generalised stratigraphic correlations between wells OW-101, OW-201, OW-301, OW-401 and OW-601.

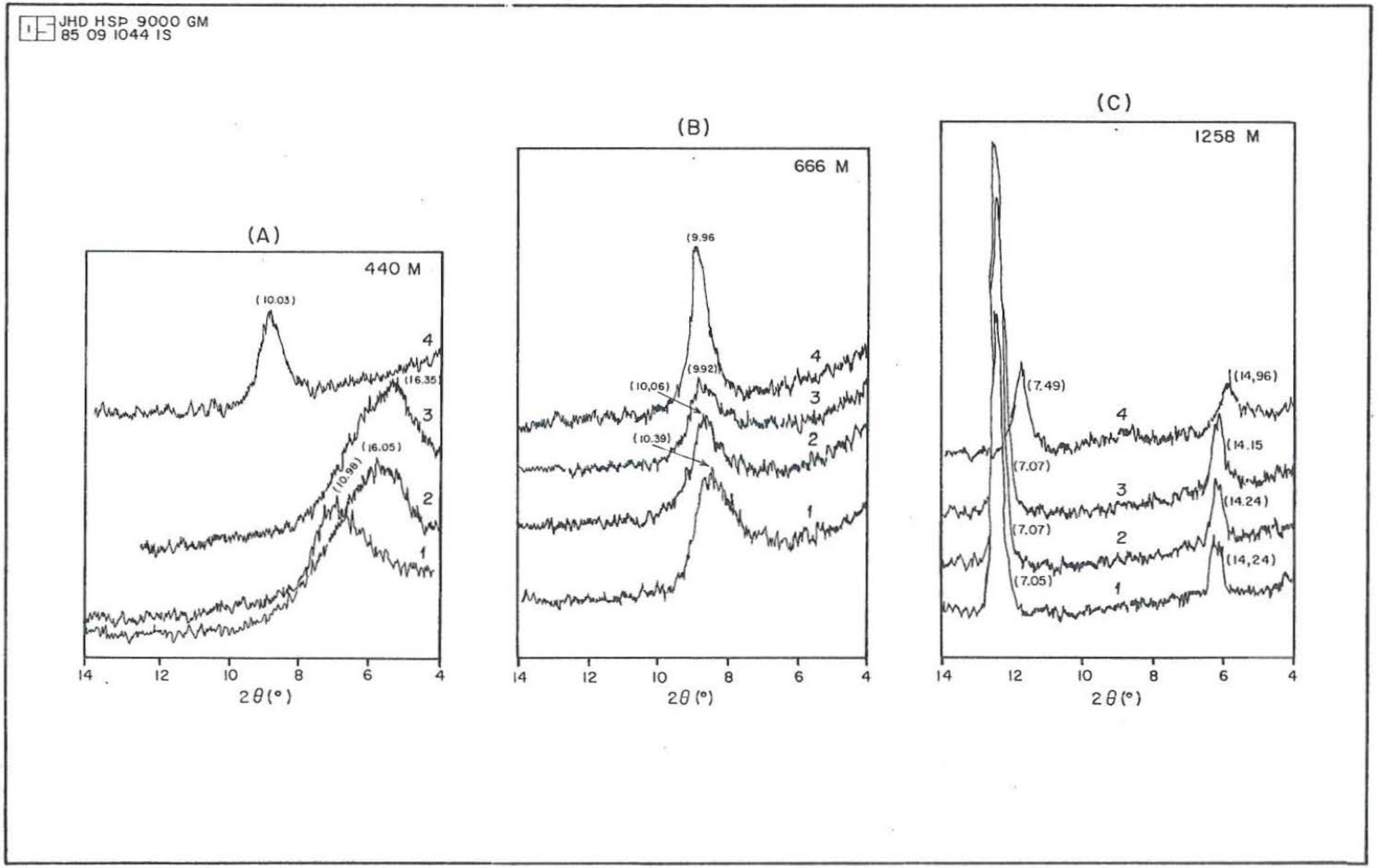

Fig. 5. Characteristic diffractograms of clay minerals.

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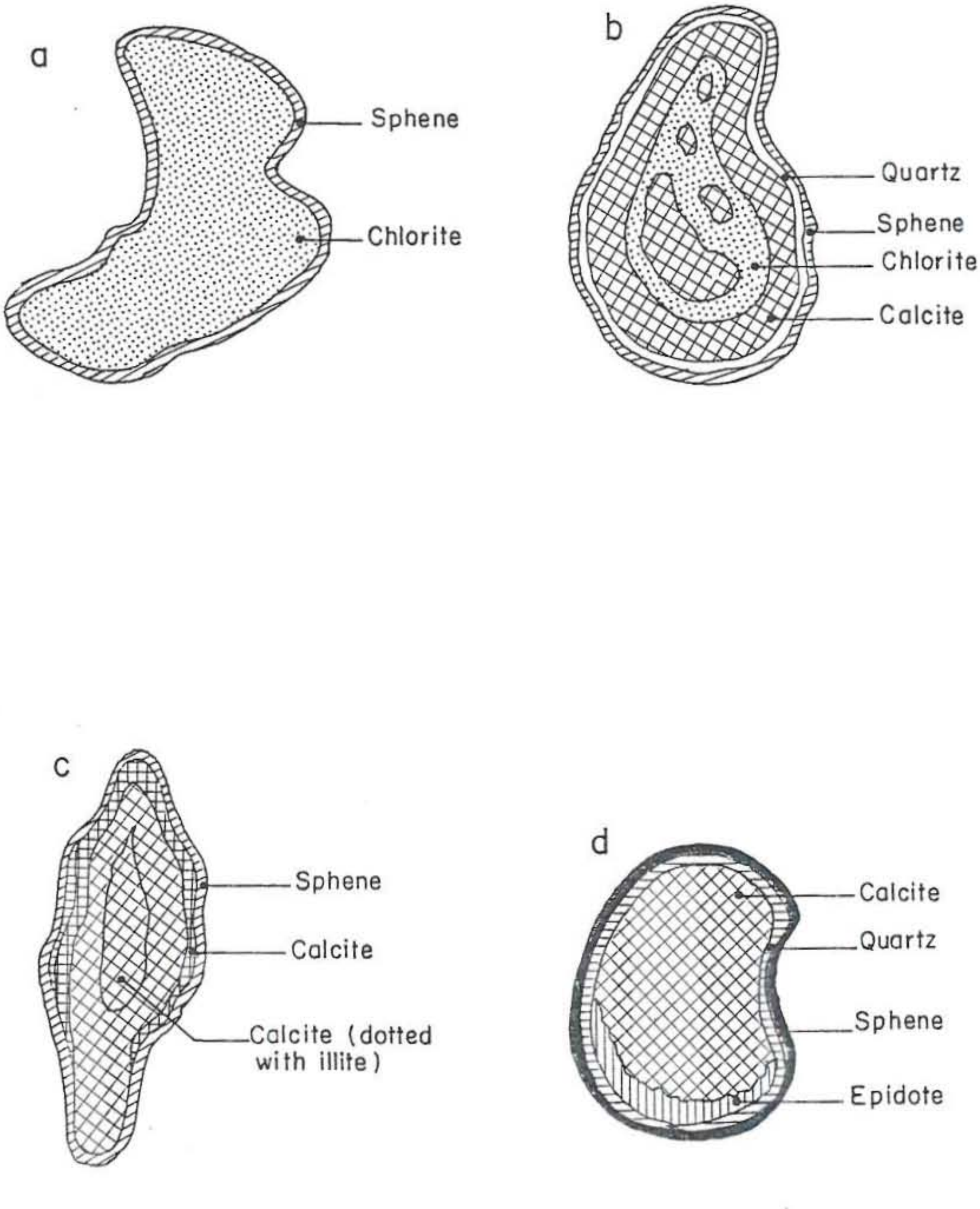

(a), (b), and (c) infillings at 1996m depth
(d) infillings at 2300m depth

Fig. 6. Vesicle infillings.

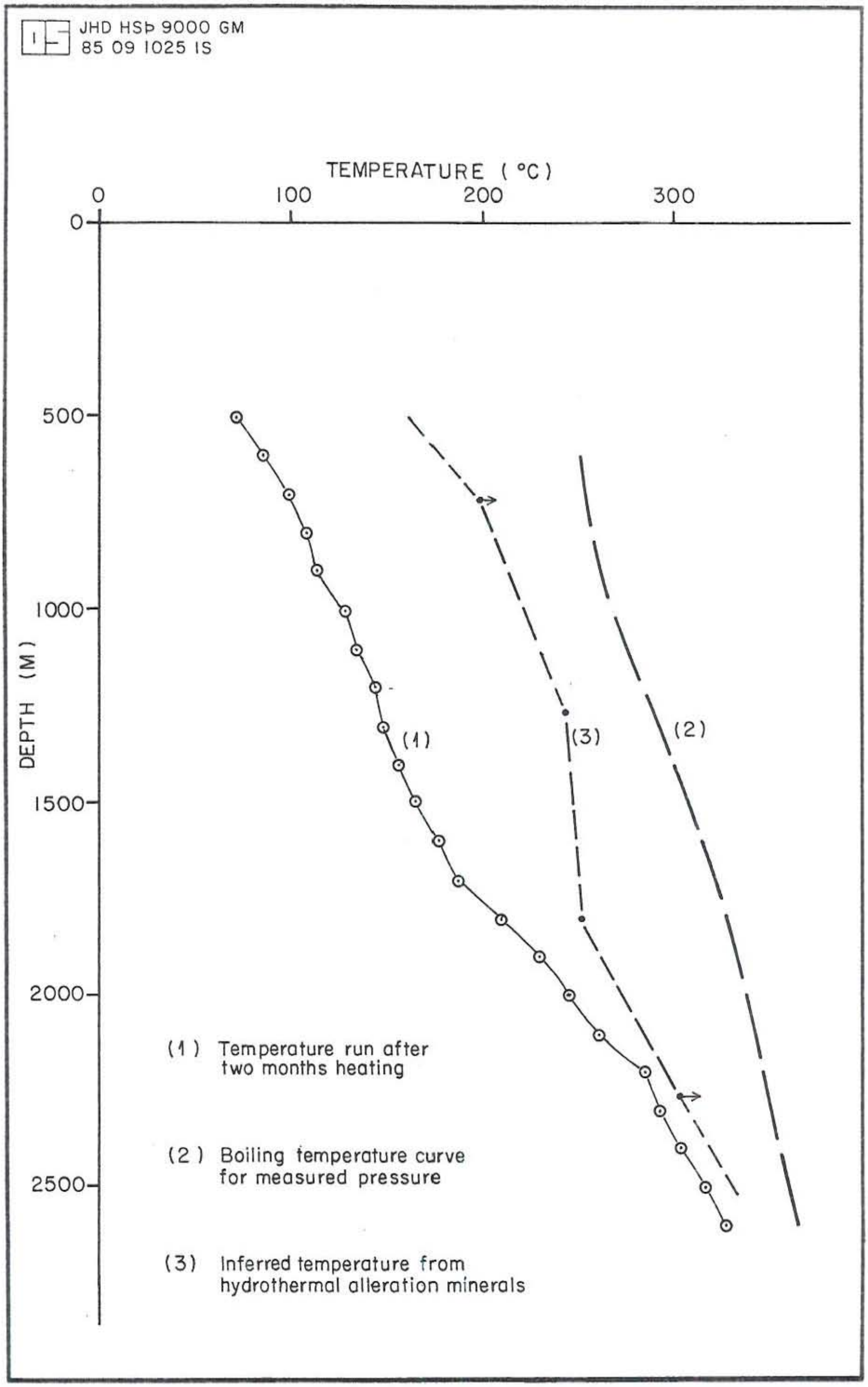

Fig. 7. Temperature profiles of well OW-601.

APPENDIX I: Clay analysis data

Depth (m)	Dried in air (Room humidity)	Air dried (Des 1) (35% humidity)	Dried in Glycol (Des 2)	Heated in oven (550°C)	Remarks
404	TB 13.18	TB 16.98	B 17.65	TB 10.04	Smectite
440	B 12.98	B 16.05	16.35	10.03	Smectite
534	25B 18 13.38, 10.04	23B 12 17.65, 10.04	32 17 17.65, 10.04	25 10.04	Smectite + illite
666	21 10.39	18 10.06	15 9.92	28 9.96	Illite
690	B 11.77	12.26	B 12.98	10.15	Smectite/ illite
740	T T 14.24, 12.44, 10.15, 7.18	B 10.15, 7.18		14 10.04	
886	12 7 10.04, 7.18	13 7 10.04, 7.10	8 T 10.04, 7.20	13 10.04	Illite + (chlorite)
970	15 10.04	15 10.15	11 5 10.04, 7.13	T 16 14.24, 10.04	Illite + (chlorite)
1176	T 13 10.04, 7.13	16 10.15, 7.13	T 10.15, 7.18	10.04	Illite + chlorite
1222	12 8 10.04, 7.13	12 7 10.04, 7.16	9 6 10.04, 7.07	13 9.92	Illite + (chlorite)
1258	14.24, 7.05	14.24, 7.07	19 50 14.15, 7.07	14.96, 7.49	Chlorite
1306	10B 10 17 14.24, 10.04, 7.12	10 11 17 14.24, 10.04, 7.10	7 8 15 14.24, 10.04, 7.07	T 11 11 14.24, 10.04, 7.49	Chlorite + illite
1366	12 9 9.92, 7.13	12 9 10.03, 7.09	T 8 7 14.24, 10.04, 7.10	T 12 7 14.24, 10.03, 7.49	(Chlorite) + illite
1436	10 13 15 14.24, 10.08, 7.13	11 14 13 14.46, 10.04, 7.09	T 12 10 14.24, 10.04, 7.13	11 15 8 14.71, 10.04, 7.49	Chlorite + illite
1472	14 13 17 14.24, 10.04, 7.13	14.24, 10.04, 7.13	10 9 14 14.24, 10.03, 7.13	15 12 T 14.30, 10.04, 7.36	Chlorite
1552	17 17 18 14.24, 10.10, 7.13	14.24, 10.03, 7.17	12 13 14 14.24, 10.04, 7.13	19B 14 14.57, 9.92	Chlorite + illite
1714	(13)B 24 14 14.24, 10.08, 7.13	14.24, 10.03, 7.09	B 17 11 14.24, 10.04, 7.13	13B 22 14.24, 9.98	Chlorite + illite

APPENDIX I: Clay analysis data, cont.

Depth (m)	Dried in air (Room humidity)	Air dried (Des 1) (35% humidity)	Dried in Glycol (Des 2)	Heated in oven (550°C)	Remarks
1810	15B 37 16 14.24, 10.09, 7.13	14.24, 10.03, 7.10	10B 28 12 14.24, 10.04, 7.15	15B 33 T 14.24, 9.98, 7.36	Chlorite + illite
2078	19 9 23 14.24, 10.04, 7.10	14.24, 10.04, 7.17	15 7 17 14.24, 10.03, 7.13	16 T 14.24, 10.04	Chlorite + (illite)
2126	29 15 39 14.24, 10.10, 7.13	14.24, 10.03, 7.13	23 11 34 14.24, 10.04, 7.13	25 17 T 14.24, 10.03, 7.13	Chlorite + illite
2162	28 T T 42 14.33, 11.32, 10.04, 7.13	14.34, 11.32, 10.04, 7.13	22 T 35 14.71, 10.04, 7.13	44 TB T 14.24, 10.04, 7.24	Chlorite + (illite)
2344	15 17 19 14.24, 10.04, 7.13	14.24, 10.13, 7.10	10 12 16 14.24, 10.03, 7.09	16 15 14.24, 10.04	Chlorite + illite
2368	22 T 29 14.24, 10.04, 7.13	T 14.24, 10.03, 7.13	22 21 14.24, 7.13	21 T 14.81, 10.39	Chlorite + (illite)
2428	20 T 21 14.24, 10.04, 7.13	14.24, 10.04, 7.13	16 T 16 14.24, 10.04, 7.13	18 T 14.24, 10.04	Chlorite + (illite)
2488	18 T 21 14.24, 10.04, 7.13	14.24, 10.04, 7.13	14 T 17 14.24, 10.04, 7.13	22 T 14.33, 10.04	Chlorite + (illite)
2500	14 T 18 14.24, 10.04, 7.13	14.24, 10.08, 7.13	18 T 23 14.24, 10.04, 7.13	22 T 14.24, 10.04	Chlorite + (illite)
2524	15 13 17 14.24, 10.04, 7.13	10B 9 13 14.24, 10.04, 7.13	15 12 16 14.24, 10.08, 7.13	15 T 13 14.24, 10.40, 10.04	Chlorite + illite
2536	11 13 12 14.24, 10.03, 7.13	8 10 10 14.24, 10.04, 7.13	11 12 11 14.24, 9.92, 7.13	11 T 12 T 14.73, 10.52, 10.04, 7.43	Chlorite + illite
2560	10 T 10 14.24, 10.03, 7.13	7 6 9 14.24, 10.04, 7.13	(9)T 7 12 14.73, 10.04, 7.13	T 14.73, 10.04, 7.37	Chlorite + illite
2572	T T 16 10 14.24, 12.09, 10.27, 7.18	T TB 12 7 14.47, 12.09, 10.27, 7.18	T TB 15 9 14.47, 12.61, 10.24, 7.22	9 10.28	Chlorite + illite
2596	12 9 12 14.24, 10.04, 7.13	9 8 9 14.24, 10.04, 7.13	12 10B 11 14.24, 10.15, 7.13	11 T 11 14.71, 10.40, 10.04	Chlorite + illite
2600	13.79, 10.22, 7.18	14.01, 10.05, 7.18	13.79, 10.22, 7.18, 6.96	T 31 13.92, 10.04	Illite + chlorite

Key: T = Trace; B = Broad peak; Numbers on top of values indicate intensity.Key: T = Trace; B = Broad peak; Numbers on top of values indicate intensity.